Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 121 (2015) 325 – 332
Procedia Engineering
www.elsevier.com/locate/procedia

9th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC) and the 3rd International Conference on Building Energy and Environment (COBEE)

Study on Ground-Test Simulation Method of the Ram Air for Commercial Airliners' Environmental Control System

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Abstract

Based on the equivalent heat transfer capacity, a closed simulation ground-test method of the ram air is proposed, it can provide the ram air's test condition for deriving the performance of commercial airliners' aircraft environmental control system (ECS). Analyzed results show that the proposed method can simulate different temperatures and pressures at the range of 0~10km flight altitudes under the compressor pressure ratio of 1.2 and turbine expansion ratio of 5. Temperatures and pressures can vary from -17.6~40℃ and 40~101kPa, respectively. In the meantime, compared to the traditional fan's simulation method, the energy consumption is decreased about 35%. By analyzing the key factors in method, it shows that altitudes and ACM characteristics can influence the power consumption and other conformance. Therefore, it needs to select ACM machine according to test requirements in engineering applications.

Peer-review under responsibility of the organizing committee of ISHVAC-COBEE 2015

Keywords: Ram air; Simulation; Equivalent heat transfer; Environmental control system (ECS)

1. Introduction

Environmental control system (ECS) is one of the most subsystems for commercial airplanes; it can keep the cabins' air pressure, temperature, humidity, air velocity, and air purity etc. in the allowable range for passengers under various flight conditions. Generally, ECS includes two branches, one is called hot side and the other is called cold side. For hot side, bleed air from engine or electric compressor is used as pressurized air source, and then enters

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Peer-review under responsibility of the organizing committee of ISHVAC-COBEE 2015
doi:10.1016/j.proeng.2015.08.1075

Nomenclature

c_p	Specific heat capacity of air，kJ/(kg•k)
$\dot{m}_t$	Mass flow of turbine，kg/s
π_t	Turbine expansion ratio
η_t	Turbine efficiency
W_t	Turbine outlet power，kW
$\dot{m}_c$	Mass flow of compressor，kg/s
π_c	Compressor pressure ratio
η_c	Compressor efficiency
W_c	Compressor consumption power，kW
η_{HX}	Heat exchanger HX efficiency
q_{m_F}	Flow rate of fan，m^3/h
ΔP	Total pressure of fan，Pa
η_0	Fan efficiency
η_1	Mechanical efficiency
W_F	Fan's power

Subscripts

1	ECS inlet
2	Compressor inlet
3	HX heat side inlet
4	Turbine inlet
5	Turbine outlet
6	HX cold side outlet

to ECS which can get depressurized/cooled/clean air for cabin; for cold side, ram air is used as the heat sink to absorb the heat form ECS. Figure 1 shows a simple diagram of ECS.

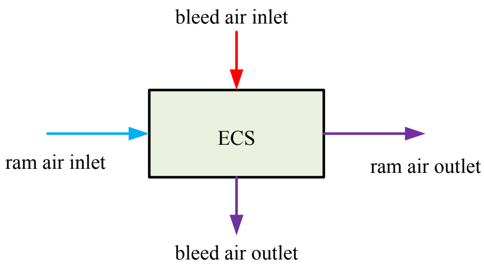

Fig. 1. Simple diagram of ECS

In the development process of the environmental control system, its performance should be tested on the ground. In other words, we need establish a test rig which including bleed air simulation test branch and ram air simulation test branch. Generally, bleed air simulation test branch usually adopts compressor for deriving the high pressure and electric furnace to maintain the high temperature, for page limitation, detailed description about it is omitted in this paper. This paper focuses on the ram air simulation test branch.

Quite a few published papers could be found about the method of the ram air simulation test branch. From the engineering experience of our research team, we chiefly use a centrifugal fan with large mass flow rate and high pressure head to simulate the test condition of the ram air simulation test branch (Zhang, 1995). Fig 2 shows the schematic diagram of the ram air simulation method by our earlier research. It can be seen that the fan just can provide the mass flow rate of the ram air; however, the temperature and pressure under different flight conditions cannot be derived.

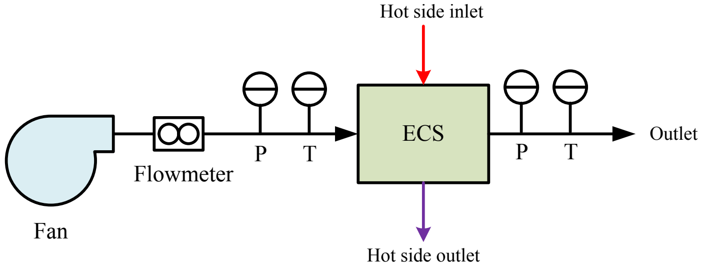

Fig. 2. Schematic diagram of the fan method

Since the flow rate of cold side is 2 to 3 times of that of ECS's hot side, for example, the mass flow rate of ram air for Concorde airliners is 4.5kg/s (Shou, 2004), the fan's power consumption is very large in order to simulate the test condition of the ram air. It also shows that the fan's simulation method is not suitable for the ground test of commercial airliners' ECS. It is necessary to find a novel way to save energy consumption.

As we know, the exchange heat of the ECS's cold side equals the product of ram air's mass flow rate, ram air's specific heat, and ram air's the temperature difference between the inlet and outlet. Thus we propose a temperature/pressure simulation method based on the equivalent exchange heat instead of fan's method based on mass flow simulation.

2. Methods

Considering the temperature and pressure of the ram air for commercial airliners may vary from -17.6~40℃ and 40~101kPa ,respectively. In order to achieve these ranges, Fig.3 shows the schematic diagram of the novel simulation unit. It is composed of an air cycle machine (ACM, Turbo-compressor), a heat exchanger (HX), a vacuum pump, a buffer tank, regulation valves, and a data acquisition system which including a flow meter, temperature sensors and pressure sensors, etc.

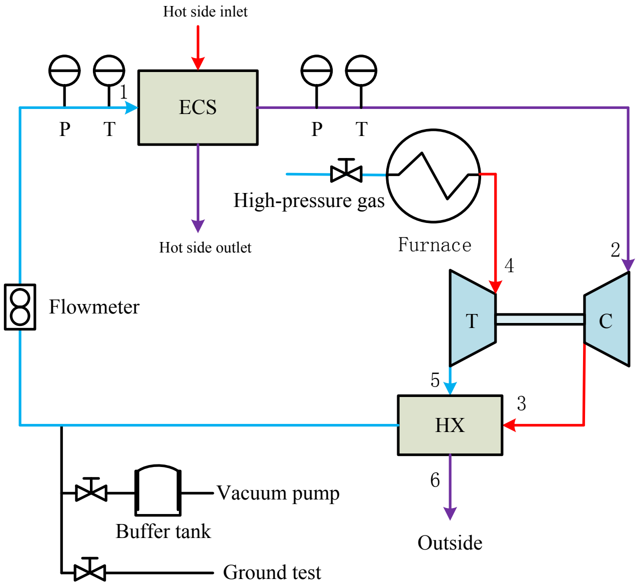

Fig. 3. Schematic diagram of the closed ram air simulation unit

Herein, high pressure gas is heated by furnace and enters the turbine for expansion. Then the gas changes into cold air which can cool the air flowing through HX within the ram air simulation branch. By adjusting the valve opening and the input power of electric furnace, the temperature of the turbine outlet gas can be regulated. Coaxial compressor is used to supplying the mass flow for ram air. The low pressure of ram air at flight conditions is provided by a vacuum pump. The inlet temperature T and pressure P of ram air in the ECS ground test can be obtained by this method. By regulating the valve, the mass flow of ram air can be adjusted.

In order to compare the performances of the proposed method and the fan method, the energy consumption of these two methods are evaluated. The calculation models of the main components are as follows (Qi, 2004; Lian, 2007).

The output power of the turbine is defined as

$$W_t = \dot{m}_t c_p T_4 \left(1 - \frac{1}{\pi_t^{(k-1)/k}}\right)\eta_t \tag{1}$$

Compressor power consumption can be expressed as

$$W_c = \frac{\dot{m}_c c_p T_2 (\pi_c^{(k-1)/k} - 1)}{\eta_c} \tag{2}$$

Fan's input power is

$$W_F = \frac{q_{m_F} \cdot \Delta P}{3600 \times 1000 \eta_0 \cdot \eta_1} \tag{3}$$

3. Results

Considering that the fan method can only simulate the ground condition, the 10km altitude condition is added and analyzed in novel method. Typical states of simulate ram air are shown in Table 1. For quantitative analysis, the components' parameters are set in Table 2(Yu, 2005).

Table 1. Typical state of simulate ram air.

Altitude (km)	Temperature(℃)	Pressure(kPa)
0	40	101
10	-17.6*	40*

*: The temperature and the pressure stand for the stagnation condition under Ma=0.85.

Table 2. Component parameters.

Component parameters	Symbol	value
Compressor pressure ratio	π_c	1.2
Turbine expansion ratio	π_t	5
Compressor efficiency	η_c	0.75
Turbine efficiency	η_t	0.8
Exchanger HX efficiency	η_{HX}	0.8

Make the following assumptions:

(1) The flow resistance of the ram air simulation branch is 20 kPa;

(2) Sum of the exchange heat flux for ECS is 22kW;

(3) The mass flow rate of the ram air simulation branch in the unit is 1080kg/h(0.3kg/s);

(4) The pipeline temperature drop and heat leakage toward environment are neglected;

(5) Turbine is in dry condition.

According to the assumption (2) and (3), the temperature raise of ram air in ECS can be calculated about 80 ℃. In engineering application, in order to prevent the excessive temperature rise, the ram air also can be precooled by other heat sink such as the ECS exhaust, water, etc. before entering the compressor. To get the ram air temperature 40℃in ground condition, the values of thermal parameters for turbine and compressor are shown in Table 3. It is noted that the mass flow rate of the high-pressure gas in turbine is 288kg/h (0.08kg/s), which can guarantee the heat balance in heat exchanger.

Table 3. Thermal parameters for key component at 0km altitude

Unit parameters	Value
Compressor inlet temperature, ℃	60
Turbine inlet temperature, ℃	60
Turbine outlet temperature, ℃	-38.3
Compressor inlet pressure, kPa	90
Turbine inlet pressure, kPa	511
Turbine power, kW	7.9
Compressor power, kW	7.2

Similarly, for 10km altitude test simulation, the values of thermal parameters for turbine and compressor are shown in Table 4. It is noted that the mass flow rate of the high-pressure gas in turbine is 234kg/h (0.065kg/s), which can guarantee the heat balance in heat exchanger.

Table 4. Thermal parameters for key component at 10km altitude

Unit parameters	Value
Compressor inlet temperature, ℃	2.4
Turbine inlet temperature, ℃	60
Turbine outlet temperature, ℃	-38.3
Compressor inlet pressure, kPa	35
Turbine inlet pressure, kPa	511
Turbine power, kW	6.4
Compressor power, kW	6.0

From the Table 3, the mass flow rate of air in the turbine is 288kg/h at 0km condition, using Eq. (2), the power consumption of compressor which provides high pressure gas can be calculated and the value is 22kW. The electric power of a furnace for getting turbine inlet temperature of 60℃ is 2.5 kW, so the total power consumption is 24.5kW. Similarly, the total power consumption is 20.4kW at 10km condition. Otherwise, for the traditional fan's simulation method, the total rejected heat flux of ECS is 22kW. To achieve the same cooling effect, the mass flow rate of fan is 1080kg/h (0.3kg/s), same with the closed simulation method. Insert this value into Eq. (3), we can get the required fan power is 37.9kW. Fan's simulation method can only simulate the ground condition, the temperature and pressure of the ram air under different flight altitudes cannot be derived. Figure 4 shows the power consumption difference between the proposed method and the traditional fan's simulation method. It can be seen that, the novel method can decrease the power consumption of 35% at ground condition.

Fig. 4. Power consumption difference

4. Discussion

In order to discuss the feasibility of the novel method, we need to analyse the key factors which may influence its performance, for example, performance change with altitudes and ACM characteristics.

4.1. Power consumption at different altitudes

For ECS experiment, the pressure and temperature change with the altitude. Low pressure can be achieved through regulating the vacuum pumps; temperature can be regulated by turbine. As we know, the ram air temperature decreases with the altitude increasing, the power consumption is reduced when the ram air flow rate keep constant (1080kg/h). In order to maintain the power balance, it is need to decrease the turbine's flow rate. The power consumption and the flow rate of the turbine changes at different simulation heights are shown in Figure 5.

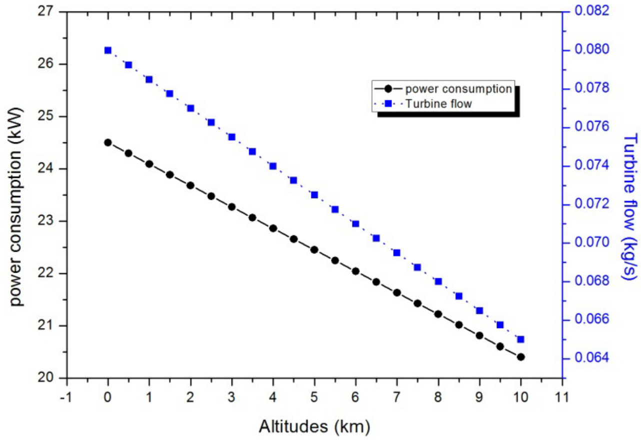

Fig. 5. Curve between altitudes and power consumption/ turbine mass flow rate

4.2. Turbine expansion ratio

The outlet temperature of turbine and the power consumption vary with its expansion ratio, in the above-mentioned analysis; we set the value of 5. Figure 6 shows the change curves among power consumption and turbine outlet temperature vary with turbine expansion ratio. When the turbine expansion ratio increases, the turbine outlet temperature reduces and the power consumption enhances. It is noted that all quantitative analysis results in this paper is only suitable for dry air condition. In the meantime, it should be considered that raising the turbine expansion ratio will increase the electric power of the compressor which provides the high-pressure gas. Therefore, the turbine expansion ratio needs to match with the requirement of the test rig.

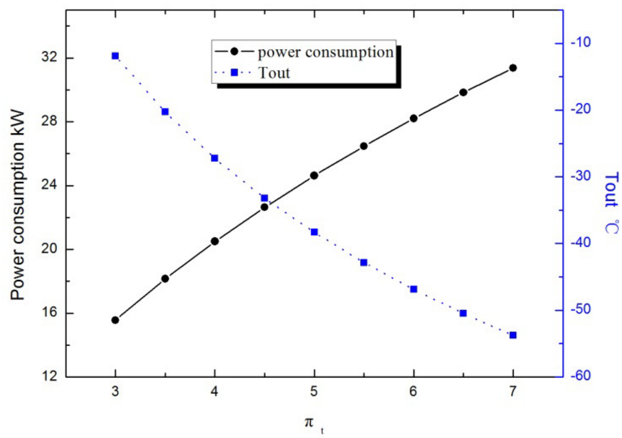

Fig. 6. Curve between the expansion ratio and output power/outlet temperature

5. Conclusion

This paper presents a ground-test method of ram air simulation for commercial airliners' ECS by using a closed unit based on an equivalent exchange heat method. It can provide different temperatures and pressures which are varied at the range of 0~10km. The details are as follows:

(1) Using the method, the temperature of ram air can be simulated for the range of -17.6~40℃ , and the range of pressure can be achieved from 40 kPa to101kPa;

(2) Ground simulation of the ram air based on equivalent exchange heat method can save power consumption about 35%, comparing with the traditional fan's method.

(3) With the simulated altitude increases, power consumption and mass flow rate of turbine both decrease; In determining the turbine expansion ratio，it is need to match with the requirement of the test rig. In this method, turbine is the key component which influences the temperature of ram air. Therefore, it should pay more attention for selecting ACM machine according to test requirements in engineering applications.

Acknowledgements

The research presented in this paper was supported financially by the National Basic Research Program of China (the 973 Program) through Grant No. 2012CB720100 and Postgraduate Practice Innovation Foundation of Beihang University (No.YCSJ-01-2014-03)

References

[1]Aircraft design manual editorial board, Handbook of aircraft design: system design of the fifteenth volumes of life support and environmental control, Bei Jing: Aviation Industry Press, 2001. [in Chinese]

[2]Environmental control system test platform feasibility demonstration, 2012. Beihang University. [in Chinese]

[3]http://www.shhuaijin.com/product_list.asp?id=293

[4] Y.M. Lian, Engineering thermodynamics. Beijing: China Architecture& Building Press, 2007. [in Chinese]

[5] X.J. Zhang, Experiment and analysis of bootstrap high-pressure water-separated ECS, Beijing University of Aeronautics and Astronautics, 1995.. [in Chinese]

[6] M. Qi, 1992. Refrigeration accessories, Bei Jing: Aviation Industry Press. [in Chinese]

[7] R.Z. Shou, H.S. He, Environmental control on aircraft. Bei jing: Bei jing University of Aeronautics and Astronautics Press, 2004. [in Chinese]

[8] J.Z. Yu, Principle and design of heat exchanger. Bei jing: Beijing University of Aeronautics and Astronautics Press, 2005. [in Chinese]

[9] X.J. Zhang, F. Li, C.X. Yang, Calculation method for matching enthalpy parameter of three-wheel bootstrap high-pressure water-separated system, Journal of Aerospace Power, 2010. [in Chinese]

[10] X.J. Zhang, F. Li, C.X. Yang, Calculating method for matching enthalpy parameter of four-wheel-bootstrap refrigeration system for civil aircraft, Journal of Beijing University of Aeronautics and Astronautics, 2010. [in Chinese]